Slips During Gait on Winter Surfaces: Evaluation of Ice Cleat Design and Slip Definition

by

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Abstract

Current winter footwear provides inadequate protection from slip-related injuries on ice, and there is limited research investigating the optimal design of anti-slip devices. This study examined how ice cleat spike height and position in the heel affect slipping. No differences could be observed between spike conditions, but results demonstrated that heel spikes may prevent slips initiated between heel contact and foot-flat and forefoot spikes may be necessary to prevent foot-flat slips. Further analysis compared slip outcomes measured using two slip onset definitions: 1) heel contact, and 2) the first point of increasing positive heel acceleration. Slip onset defined as time of heel contact overestimated the number of slips and slip distances. These results demonstrate that ice cleats have the potential to protect pedestrians from slipping but some styles available to consumers (i.e. heel spikes only) may not be adequate. Choice of slip definition in footwear evaluations can significantly influence study outcomes.
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Chapter 1
Introduction

1.1 Motivation

Slip and fall accidents on icy and snowy surfaces are common for pedestrians and outdoor workers during winter (Gao et al. 2008; Grönqvist and Hirvonen 1995; Bentley and Haslam 2001). In Nordic countries, slips are attributed to 43% of all falls and 16% of accidents at work, home and during leisure activities, and two thirds of these slips are on surfaces covered with ice and snow (Lund 1984). Slips leading to falls are a major cause of serious injury and can result in lost-time costs to employers when they occur in the workplace. Data from the Canadian Institute for Health Information show that over 21,000 Ontarians visited an emergency department for injuries from falls occurring on the same level involving ice and snow in 2005-06 (Ontario Injury Prevention Resource Centre 2009) and the city of Toronto alone has paid $14 million for icy sidewalk slip and fall claims from 2005-2010, with an additional $33 million in outstanding claims (Auditor General's Office 2011). In 2002-03 approximately one third of emergency room visits for injuries related to falls on ice were for individuals between 60-79 years of age (Canadian Institute for Health Information 2005). There is also evidence that workers over the age of 45 have more falls on ice and snow and have longer absences after accidents (Kemmlert and Lundholm 2001). As the population ages it is likely that the frequency and severity of winter slips and falls will increase unless effective interventions are developed.

There are a number of factors that contribute to the initiation of a slip and the gravity of its outcome, including individual gait biomechanics, physiological and psychological factors, properties of footwear and the underfoot surface, and environment (Gao and Abeysekera 2004). However, the major risk factor for slips is low friction between footwear and the walking surface. Footwear design is, therefore, an important consideration in reducing the number of slip accidents (Gao et al. 2008; Aschan et al. 2009; Grönqvist 1999). However, the majority of slip research focuses on indoor surfaces and there is limited research investigating the impact of footwear design on slips on winter surfaces such as ice. This is
surprising considering the number of slip and fall accidents is highest in the winter (Gao and Abeysekera 2004; Aschan et al. 2009). Studies using questionnaire surveys and discussion groups with outdoor workers have shown that they consider weather, temperature, and protective clothing and gear as important work and health issues (Lowe et al. 2003). Anti-slip winter footwear devices have the potential to prevent the risk of slips and falls on ice and snow (Gard and Lundborg 2000) but devices that have previously been developed do not provide adequate slip-resistance over a range of surface conditions from both objective and subjective evaluations (Gao et al. 2008; Bruce et al. 1986; Gard and Berggard 2006). The design and performance of winter footwear requires more attention in order to protect pedestrians and outdoor workers (Bentley and Haslam 1998).

Slip distance has been identified in the literature as an important measure for assessing the severity of a slip (Tsai and Powers 2013; Brady et al. 2000; DiDomenico et al. 2007; Strandberg and Lanshammar 1981; Cham and Redfern 2002a). Slip distance is measured as the displacement of the heel from slip onset to slip end. Slips are often categorized as ‘microslips’, which have small displacements and can occur even on non-slippery surfaces without the participant noticing, or ‘macroslips’, which can include slip-recovery trials with or without major gait disturbances or slips resulting in falls (Cham and Redfern 2002a; Strandberg and Lanshammar 1981; Leamon and Li 1990). Slips generally occur at either heel contact when the foot first contacts the ground or at toe-off as the foot pushes off. Heel contact is considered the more critical point of gait because slips are more frequent and have more dangerous outcomes as they can lead to a backwards fall (Gao and Abeysekera 2004; Grönnqvist 1999). A qualitative study measuring participants’ perception of stability during gait on slippery winter surfaces showed that the most important location for traction elements in anti-slip devices may be towards the rear of the heel where they can prevent the initiation of a dangerous heel slip (Gard and Berggard 2006).

Developing winter footwear that has increased slip-resistance on variable winter surfaces will provide outdoor workers and pedestrians with greater protection from the risk of winter slip and fall accidents. It is also important to evaluate current slip definitions to
identify the most robust and relevant technique for assessing slips. This will ensure that the most meaningful methods are used to evaluate footwear designs.

1.2 Thesis Objectives

Based on the literature describing slips and falls in winter, there is no single type of winter footwear or anti-slip device that provides users with adequate protection on a variety of winter walking surfaces. There is also a lack of research examining how the general design of anti-slip devices impacts their utility. One aim of the present research is to examine optimal characteristics for spikes on the sole of winter footwear to prevent slipping on icy surfaces. Given that heel contact has been described as the most critical phase of the gait cycle in terms of slip risk, the specific goals of the study are to characterize how changes in spike position and height on the heel of footwear affect walking patterns and slipping on level icy surfaces as well as icy slopes. It is expected that taller spikes close to the rear of the heel may provide the most protection from slipping at heel contact.

One important method for evaluating the effectiveness of winter footwear designs is examining the kinematics of the heel during gait on slippery surfaces. Parameters like slip distance can be used to determine slip frequency and severity, thereby giving an indication of the relative safety of different types of footwear tested. However, there are different approaches used in the literature to identify and measure slips. An additional aim of this thesis is to compare different definitions of slip onset applied to the same gait data and evaluate the effect of measurement technique on slip outcomes.

The methodology developed in this study will provide a basis for future work examining anti-slip footwear designs with the aim of developing guidelines to improve anti-slip winter footwear. The comparison of different analysis techniques will highlight discrepancies between slip studies and offer insight into possible improvements in slip measurements.
Chapter 2
Review of Literature

2.1 Introduction to Slips

There are numerous factors contributing to slips and falls including individual gait biomechanics, physiological and psychological factors related to gait, characteristics of the underfoot surface, properties of footwear and the interaction between footwear and walkway, and environment (Tisserand 1985; Gao and Abeysekera 2004). However, there is agreement in the literature that the major risk factor for slips is poor grip or low friction between footwear and the walking surface (Grönqvist and Hirvonen 1995; Gao et al. 2008; Aschan et al. 2009; Abeysekera and Gao 2001; Grönqvist 1999).

Slips generally occur at either heel contact - in a forward direction - or at toe-off in the rearward direction; these are the two points of the gait cycle where shear forces are highest and are near periods of gait where the centre of mass passes outside the base of support, increasing the risk of instability (Gao and Abeysekera 2004; Winter 1995). Heel contact is considered to be the more critical phase in the walking cycle in terms of slip risk because slips are more frequent and dangerous (Perkins 1978; Strandberg and Lanshammar 1981; Leamon and Son 1989; Manning et al. 1991; Redfern and Dipasquale 1997; Grönqvist 1999). Slipping at heel contact can result in a forward slip on the leading foot, which is likely to cause a backwards fall since forward momentum of the body keeps body weight on the slipping foot (Grönqvist et al. 2001). The severity or outcome of a slip is dependent on the person's postural control and ability to adjust their gait and regain balance (Brady et al. 2000; You et al. 2001).

2.2 Slip Measurement

The interaction between the footwear sole and underfoot surface is a key factor to consider in winter footwear design. Measurements of footwear slip-resistance and the frequency and severity of slips can include evaluations of coefficient of friction between the footwear and walkway surface and/or analysis of the kinematics of gait on slippery surfaces.
2.2.1 Friction

Slip-resistance is often measured as the dynamic coefficient of friction between the footwear sole and underfoot surface (Aschan et al. 2009; Grönqvist and Hirvonen 1995; Gao et al. 2004). There are two general approaches to measuring the friction between footwear and the walkway surface: the use of mechanical slip-meters, also called tribometers, and biomechanical studies using force plates to record ground reaction forces on participants’ feet as they traverse a walkway.

2.2.1.1 Tribometers and Slip-Resistance Standards

Numerous tribometers have been developed to measure either the static or dynamic coefficient of friction at the footwear-walkway interface. Many devices are not considered valid or reliable because they do not realistically reproduce the forces and motions involved during human gait and slips and cannot generate reproducible measures (Strandberg and Lanshammar 1981). Tribometers may also use a test foot material that is different from the material of the footwear being examined in the same study (Burnfield and Powers 2006). Different test devices can give measurements that do not agree, even under identical conditions, and using the same test device under identical conditions can sometimes produce variable results (Burnfield and Powers 2006; Di Pill and Vidal 2002).

There are major challenges in determining standards for slip-resistance of winter footwear. Most slip and fall research focuses on accident prevention on indoor surfaces, where reproducible measures of slip-resistance are already challenging (Jung and Fischer 1993) whereas outdoor surfaces are more variable and environmental factors are harder to control and reproduce (Redfern and Bidanda 1994). In addition, there is some disagreement on the proper procedure or device used for measuring the coefficient of friction in order to quantify the slip-resistance.

As a result of the difficulty in measuring slip-resistance and a lack of agreement between the results of various test devices there are only general guidelines for the recommended
The coefficient of friction for footwear to prevent slips. In the recently updated standards for personal protective footwear the Canadian Standards Association does not specify a minimum slip-resistance that must be met; rather the guidelines say that any footwear being identified as slip-resistant must perform a SATRA slip-test (ISO 13287 test method) and label their footwear with the results (Plant Engineering & Maintenance 2009). The SATRA device uses surfaces such as dry quarry tile and quarry tile and stainless steel wetted with distilled water. Although SATRA can also measure slip-resistance on additional surfaces such as ice it is not a requirement in the slip-resistance standards. There are currently no standards developed specifically to measure the slip-resistance of anti-slip devices such as spiked footwear as the ISO standards are not applicable.

### 2.2.1.2 Biomechanical Measures

The results of mechanical slip-resistance tests may not accurately reflect footwear performance in real conditions, and therefore human-centred testing has been the focus of numerous slip-resistance studies.

Ground reaction forces at the shoe-floor interface are one of the commonly examined biomechanical factors in slips. *Utilized coefficient of friction* is defined as the ratio of the shear to normal foot forces that are generated during normal locomotion when no slips occur. The peak utilized coefficient of friction between heel contact and mid-stance is typically the value used to approximate the minimum available coefficient of friction that the footwear-walkway interface would need to have to prevent slipping (Hanson et al 1999; Redfern et al. 2001; Buczek and Banks 1996; Redfern and DiPasquale 1997; Strandberg 1983; Burnfield and Powers 2006) and has been suggested as an indicator of slip potential (McVay and Redfern 1994; Buczek and Banks 1996). *Available coefficient of friction* is measured as the coefficient of friction during trials where slips occurred (Redfern et al. 2001) or can be estimated using a tribometer to measure the dynamic coefficient of friction (Hanson et al. 1999; Burnfield and Powers 2006). Slips generally occur when the utilized coefficient of friction exceeds the estimated available coefficient of friction. Hanson et al. (1999) demonstrated that as the difference between available and utilized coefficient of friction decreased (i.e. the friction used during gait approached or exceeded the estimated
friction available) more slip and fall events were observed. Trials with lower available coefficient of friction were typically associated with increased slip severity and falls (Strandberg 1983; Grönqvist et al. 1993; Hanson et al. 1999).

2.2.2 Kinematics

Motion capture systems are used to track the position of the foot during gait in order to measure kinematic parameters such as slip distance and velocity, foot-floor contact angle and step length. These variables can be indicators of slip severity as well as confidence during gait. However, the literature varies in the definition of a slip or fall based on kinematic data, with differences in foot tracking and contact events contributing to the discrepancies in reported studies.

2.2.2.1 Slip and Fall Definitions

In the literature there is an understanding that heel sliding can occur at and soon after heel contact even during gait on dry, non-slippery surfaces. The heel is most often sliding forwards at heel contact, and can reverse direction to slide backwards before sliding forward once again and eventually stopping (forward-backward-forward slide). Occasionally the heel is already sliding backwards at heel contact and then slides forward before stopping (Cham and Redfern 2002a; Perkins 1978; Strandberg and Lanshammar 1981). Heel sliding with small displacements on slippery or non-slippery surfaces is generally referred to as a microslip and is not detected by participants, while larger slips that can include a slip-recovery trial with or without major gait disturbances or a slip resulting in a fall are termed macroslips. Threshold slip distance values of 1 cm (Perkins 1978) or 3 cm (Leamon and Li 1990) have been suggested, above which the step is considered a macroslip. These cut-off values have also been used by other researchers whose experimental procedures differ from those used to identify the threshold values (Cham and Redfern 2002a; Cham and Redfern 2001; DiDomenico et al. 2007; Chambers et al. 2003; McGorry et al. 2007).

Slip distance is a useful measure of the relative danger of slips as it has been shown to
increase with slip severity, where severe slips are those leading to falls (Cham and Redfern 2002a; Tsai and Powers 2013; Brady et al. 2000; DiDomenico et al. 2007; Lockhart et al. 2000; Strandberg and Lanshammar 1981). Severe slips are those leading to falls, while The slip distance is measured as the horizontal heel displacement from slip onset to slip end. Most commonly, slip onset is defined by the instance of heel contact while slip end is the point at which the heel velocity reaches approximately zero (Brady et al. 2000; Cham and Redfern 2002a; Liu et al. 2013; Moyer et al. 2006; DiDomenico et al. 2007; Burnfield and Powers 2006; Troy and Grabiner 2006). Based on this definition an accurate determination of heel contact is fairly important. Various definitions of heel contact are outlined in the following section. An alternative definition for slip onset is the point where there is a positive increasing horizontal acceleration of the heel after heel contact with the heel moving in a forward direction (Lockhart et al. 2000; Strandberg and Lanshammar 1981), or equivalently the first minimum of the horizontal heel velocity after heel contact, as shown in Figure 1. Lockhart et al. (2000) divided the slip distance into an initial slip distance and ‘slip distance II’ to create separate measures of 1) slip initiation and 2) slip behaviour after slip initiation. Initial slip distance was measured from slip onset to the peak heel acceleration (‘mid slip’) and ‘slip distance II’ was measured from that peak acceleration to the following maximum of the horizontal heel velocity (Figure 1).
Figure 1: The slip onset definition used by Lockhart et al. is the positive horizontal heel velocity or first minimum of the horizontal heel velocity, shown as the slip start point in a) and b) respectively (Lockhart et al. 2000).

In laboratory-based studies, a fall is defined as either a step where the heel does not come to a stop after heel contact or a trial where the subject loses balance and eventually falls into the safety harness (Cham and Redfern 2002a; Hanson et al. 1999; Brady et al. 2000; Moyer et al. 2006; Cham and Redfern 2001). Some studies also use thresholds of 10 cm and 50 cm/s for the slip distance and slip velocity, respectively, in their criteria for considering a slip a fall, ‘likely fall’ or ‘full slip (DiDomenico et al. 2007; DiDomenico et al. 2005; Lockhart and Kim 2006; Grönnqvist et al. 2003a; Grönnqvist et al. 2003b). These thresholds are used because beyond these limits slips were observed to have resulted in loss
of balance (Perkins 1978; Strandberg and Lanshammar 1981). However, the work of others has demonstrated that these thresholds for slip distance and velocity may not be an accurate representation of the upper limits for slip recovery because many individuals were able to recover from slips with distances larger than 18 cm. Nevertheless, longer slip distances and higher slip velocities were more likely to result in a fall (Brady et al. 2000). It should be noted that the definition of slip onset used by Strandberg and Lanshammar (1981) which resulted in this fall threshold was the time of the first minimum of the heel’s forward velocity, which differs from the slip start definition of heel contact that many papers use. The use of a 10 cm threshold for a likely fall by other researchers could be misleading if there was any inaccuracy in heel contact definition, as this might result in slipping being measured before the minimum forward velocity was reached.

2.2.2.2 Heel Contact Definitions

The gold standard for determining heel contact is to use force plates and recorded ground reaction forces. Heel contact is defined as the point in time where the vertical force exceeds a threshold, often chosen as a value between 5N to 10N in order to clearly differentiate the onset of loading from signal noise during unloaded conditions (Lockhart et al. 2003; Lockhart and Kim 2006; Burnfield and Powers 2007; McGorry et al. 2007), although other thresholds have also been used to differentiate between heel contact and noise (Hanson et al. 1999; Cham and Redfern 2002a; Moyer et al. 2006; Beschorner et al. 2013; Osis et al. 2012). Several studies have also used kinematic data parameters, such as the vertical position or velocity of the heel, on their own or in combination with force plate data to identify heel contact (Chambers et al. 2003; Brady et al. 2000). However, specific thresholds used to determine heel contact are not always given for the force plate and kinematic measurements (Brady et al. 2000; Beschorner and Cham 2008) with many studies providing no indication of how heel contact was identified (Strandberg and Lanshammar 1981; DiDomenico et al. 2007; Burnfield and Powers 2006).
2.2.2.3 Foot Landmarks

When slip onset is defined as the point of heel contact (i.e. when the foot has likely not yet rotated to flat), the choice of heel location becomes an important consideration because it could influence the measured horizontal displacement of the heel during foot rotation. Various marker locations are used to track the position of the foot during gait on slippery and non-slippery surfaces. Generally markers are placed at the heel and toe in order to allow for foot-floor angle to be measured, although in many cases only the heel is tracked. For trials where the participant walks barefoot, anatomical locations such as the posterior calcaneus and fifth metatarsal head (Brady et al. 2000) have been used. In shod experiments, marker locations are generally near the lateral heel and toe of the shoe and occasionally near the fifth metatarsal and malleolus (Cham and Redfern 2002a; Cham and Redfern 2002b; Moyer et al. 2006; Hanson et al. 1999; Strandberg and Lanshammar 1981; Cham and Redfern 2001; DiDomenico et al. 2007; Chambers et al. 2003). The heel location used for calculations such as slip distance and heel velocity is either defined relative to the positions of the tracked foot markers (Cham and Redfern 2002a; Moyer et al. 2006) or is set to the position of one tracking marker located on the heel (Lockhart et al. 2002; Burnfield and Powers 2006). The heel landmark used by different studies for analysis varies from the bottom of the heel, approximating the point of contact with the walkway, to several centimetres above the bottom of the heel (Lockhart et al. 2002).

2.3 Slips and Falls in Winter

The number of slip and fall accidents is highest in the winter and two thirds of slips occur on surfaces covered by ice or snow (Gao and Abeysekera 2004; Grönqvist and Hirvonen 1995; Gao et al. 2008; Aschan et al. 2009). Although falls occur on numerous winter surfaces, there is an increased incidence of falls on ice covered with snow, likely because individuals are unable to predict the slippery underfoot conditions and adjust their gait accordingly (Gao et al. 2008). It has also been demonstrated that wet ice is much more slippery than hard ice (Gao et al. 2003; Grönqvist and Hirvonen 1995). Variable properties of the surface such as the ice structure, hardness and temperature and the thickness of the
water layer can all greatly affect the friction during a slip (Grönqvist and Hirvonen 1995).

Normal snow clearance has not reduced the number of falls experienced by pedestrians in wintertime (Berggard and Johansson 2010). Many types of winter footwear use specific soling materials and special treads to improve traction in slippery conditions. Alternatively, using attachable anti-slip devices on ordinary shoes is another means of preventing slips and falls on icy and snowy surfaces and there are many personal footwear devices available to pedestrians and outdoor workers for protection on slippery surfaces. Examples include ice cleats (Gard and Berggard 2006), chains (Bruce et al. 1986) and the Yaktrax walker, which consists of elasticized bands of steel coil that cross the length of the foot (McKiernan 2005).

2.4 Winter Footwear and Anti-Slip Devices

It has been shown that the slip-resistance of footwear can be affected by numerous properties of the sole such as material, hardness and roughness. The type and location of traction elements on an anti-slip device are also important. For example using steel-coiled elastics versus metal studs or placement of traction elements under the heel, toe or whole foot will potentially alter the likelihood of a slip occurring or the ability to recover from a slip.

2.4.1 Footwear Sole

Many different characteristics of footwear soling are thought to influence slip-resistance, including roughness, material, hardness, contact area, tread design and level of wear (Jung 1992; Gao and Abeysekera 2004). It has been shown that footwear sole abrasion by natural or artificial means has no significant effect on coefficient of friction on melting ice, but was attributed to significantly higher slip-resistance on hard ice (Gao et al. 2003). Treads with higher contact areas are thought to be more slip-resistant (Leclercq et al. 1994; Tisserand 1985) and are recommended to have open channels to allow pollutants like water to be evacuated from under the shoe (Strandberg 1985; Tisserand 1985). Shoes with softer sole materials have demonstrated the highest frictional forces on dry ice, although they still did
not give adequate friction values to provide protection from slipping accidents on wet smooth ice (Bruce et al. 1986; Grönqvist and Hirvonen 1995). No soling material has been shown to be adequately slip resistant on both dry and wet ice (Gao and Abeysekera 2004).

2.4.2 Winter Anti-Slip Devices

In one of the few studies to investigate anti-slip winter footwear design, Gard and Berggard (2006) tested three different general configurations of anti-slip devices: a heel device, with metal studs under the heel; a foot-blade device, with metal studs under the ball of the foot and toe; and a whole-foot device, with chains crossing the entire length of the foot. Subjects walked on various surface conditions, including pure ice and ice covered with sand, gravel, snow, or salt, and were asked to rate their walking safety and balance and their perception of each device. Subjects found the heel device to be the safest on all five surfaces examined, followed by the toe device and finally the whole-foot device (Gard and Berggard 2006). The heel device was likely perceived to increase stability because early heel contact is one of the most important parts of the walking cycle when considering stability and risk of slipping (Redfern et al. 2001). However, the results of the study are limited by the fact that the devices did not use identical traction elements, as the heel and foot-blade devices used metal studs while the whole-foot device used chains.

The utility of anti-slip devices is often limited to certain surface conditions, as there is no single type of winter footwear or anti-slip device that provides adequate protection from slipping on a variety of winter surfaces. An early study of the slip resistance of footwear indicated that chains gave poor traction on dry ice although they were effective on snow, and ice cleats gave better traction on dry ice (Bruce et al. 1986). A study by Grönqvist and Hirvonen (1995) using a step simulator apparatus concluded that footwear with the largest possible apparent contact area between the sole and ice, using flat-based tread projections, were recommended for dry ice. Footwear that combined harder heel materials and sharp (e.g. conic) tread projections were found to give better friction readings on wet ice because they created scratches on the surface. Footwear that achieved the highest coefficient of friction on wet ice also had the lowest coefficient of friction on dry ice (Grönqvist and Hirvonen 1995). Finally, studies looking at the Yaktrax Walker anti-slip device found that
although it is effective for use on snow-covered surfaces, it can actually be a hazard if used indoors or when descending dry, hard slopes (McKiernan 2005).

Although there is a demonstrated need for improvements to current anti-slip devices, their use has still been linked to a reduction in the number of winter accidents due to slips and falls. In a study with 109 seniors randomized between a control group and a group provided with the Yaktrax walker to wear, the anti-slip device was shown to potentially reduce the risk of winter falls for older adults with a history of previous falls (McKiernan 2005). Providing outdoor workers with access to anti-slip devices has also been shown to potentially reduce their risk of injury and accident rates. A study looking at workers in four different organizations (a newspaper delivery service, a military regiment, a mining company and a construction company) found that those groups that were provided with professional anti-slip footwear showed lower risks for slips and falls (Gao et al. 2008).

Overall, neither winter footwear nor anti-slip devices have been shown to be adequate in slippery conditions. Although the outdoor workers provided with protective footwear in the study by Gao et al. (2008) experienced a lower risk of falls, they were still unsatisfied with the anti-slip properties of the footwear (Gao et al. 2008). Other studies looking at user satisfaction with anti-slip devices have shown that they are often considered inadequate in terms of safety or comfort (Hara et al. 1997; Gard and Berggard 2006), and subjects have also reported problems using anti-slip devices on ice with snow because the snow can become trapped between the shoe and device and interfere with the normal functioning of the anti-slip device (Berggard and Johansson 2010). Quantitative studies have also shown that many winter footwear designs provide insufficient slip-resistance to protect users from slips and falls (Aschan et al. 2009; Gao et al. 2003). The effectiveness of footwear is highly dependent on the surface conditions, and there does not appear to be one type of winter footwear or anti-slip device that performs well on numerous surfaces.

2.5 Research Gap

There are two areas of winter slip research that have received little attention in the literature: the design of anti-slip devices such as ice cleats, and particularly the effects of
characteristics like location and height of spikes on slipping, and the definition of a slip. These two topics are discussed further below.

2.5.1 Winter Anti-Slip Devices

Based on the literature, there is no single type of winter footwear or anti-slip device that provides users with adequate protection on a variety of winter underfoot conditions. Since pedestrians and outdoor workers must traverse highly variable surfaces in the winter, it is not adequate to have footwear that provides slip-resistance on, for example, either dry ice or wet ice. In addition, there is a lack of research investigating how different design characteristics of anti-slip devices, such as the configuration and properties of traction elements, affect their performance on slippery winter surfaces. Specific to ice cleats, positioning and height of spikes may impact slipping. By studying the impact that different anti-slip device properties have on slipping, general guidelines can be developed for the improvement of future winter footwear and gait stabilizing devices to protect pedestrians from slip and fall injuries.

2.5.2 Biomechanical Slip Studies

One important method for evaluating the effectiveness of winter footwear designs is examining the gait of participants during different footwear-walkway combinations and measuring the kinetics and kinematics of the heel during slips and non-slips. Measurements of variables such as number of slips and slip distance can give an indication of slip severity, and therefore the relative safety of each footwear design. However, there are several inconsistencies in the measurement of slips across studies that may impact footwear evaluations, such as the definition of heel position and heel contact, and the definition of slip onset.

Various studies choose different locations on the heel for attaching motion capture markers and either use one marker to define the heel position or define a virtual heel position relative to these tracking markers. These same studies use a slip onset defined as the instant of heel contact and apply a slip distance threshold (e.g. 1 cm) to determine
whether a step is a slip. However, different choices of heel location could impact the magnitude of the slip distance. If the heel is chosen as a point in contact with the ground when the foot is flat on the walking surface instead of a point several centimetres higher on the participant’s foot (Lockhart et al. 2002) there may be less heel displacement resulting from foot rotation (Figure 2 and Figure 3). In this case, slip distances would appear smaller for the heel landmark that comes into contact with the walkway. For example, assuming an average heel contact angle of approximately 20° for gait on level ground (Cham and Redfern 2002b) and a heel landmark located on the rear of the boot 3 cm higher above the ground (point B in Figure 3) the horizontal component of foot rotation would exceed the 1 cm threshold used by many studies to classify a step as a slip. When these slip thresholds have been determined from previous experiments where the heel was defined as the ‘heel tip’ or rear bottom portion of the heel (Perkins 1978) it would stand to reason that if a different heel definition was used the resulting increase in slip displacement could lead to the misclassification of steps as slips.

Figure 2: Heel landmark locations at the bottom of the heel (A) and several centimeters higher (B).
**Figure 3:** Illustration of horizontal displacement resulting from foot rotation from heel contact to foot flat for each heel landmark location shown in Figure 2 (above). The dashed line represents the foot at heel contact, while the solid line represents the foot once it has rotated to flat.

In addition to the choice of heel landmark, the definition of slip onset may have a large impact on measured slip distances. The typical definition of slip onset is the time of heel contact, but some studies have instead used the first point following heel contact with increasing positive horizontal heel acceleration (in the forward direction) to define slip onset. Since the former definition of slip relies heavily on accurate identification of heel contact, which is often not defined consistently between studies and can be difficult to accurately determine when force plates are not available for use in experiments, the use of heel horizontal acceleration may provide a more conservative estimate of slip start. A comparison of slip distances using each slip onset definition would provide a useful start in determining whether more robust definitions of slip are needed and evaluating the relevance of current slip measurement techniques.
Chapter 3
Methods

3.1 Participants

Six participants (four female, two male) with no known mobility limitations who were between the ages of 22-45 were recruited for the study (mean age: 27 years (SD 3 years); mass: 63.4 kg (SD 10.5 kg), height: 1.7 m (SD 0.1 m)). Older adults have increased risk of cardiac strain after being exposed to cold ambient temperatures, with decreased thermoregulation and cold tolerance (Collins 1991; Mathew et al. 1986), thus only younger participants were recruited for the present study for safety reasons. To be included in the study participants were required to normally walk outdoors in winter conditions and be able to ambulate for at least 20 consecutive minutes without the use of a mobility aid. Participants were excluded if they used any medications or drugs that would affect their balance or mobility or presented with pulmonary or cardiovascular health conditions. Ethics approval for the study was obtained from the TRI-UHN Research Ethics Board, and participants gave written informed consent prior to study participation.

3.2 Experimental Variables

There is a wide range of ice cleat design variables that could be studied to determine their effect on gait on winter surfaces. However, since experiments were performed in a cold environment it was essential to limit the number of trials and the amount of time subjects spent in the laboratory for safety reasons and to minimize fatigue. Consequently, the present study focuses on the position and height (protruded length) of the spikes and how each parameter affects gait on slippery winter walkways.

Based on previous literature, anti-slip devices placed under the heel, toe and full foot perform differently, and devices with traction elements under the heel only may be the most effective (Gard and Berggard 2006). Heel contact has also been identified as the most critical gait phase where slips are more likely to result in falls (Hanson et al. 1999; Strandberg 1983). Therefore the current study examined only the optimal configuration for
spikes in the heel.

The placement of the spikes in ice cleats is an important experimental factor because their location could impact slipping if they are too far from the back of the heel at heel strike (Redfern et al. 2001). Two spikes were used on each heel and the placement of spikes was symmetrical across the midline of the sole. The positions of the spikes were scaled for each sole size such that the distance of the spikes from the edge of the sole as a percent of total heel width and length remained constant between footwear sizes. The spike positions that were investigated are illustrated in Figure 4: a) two spikes placed midway between the front and back edges of the heel and b) two spikes located at the back edge of the heel.

![Figure 4: The spike positions tested are shown with black circles to represent spike placement on the boot heel: (a) two spikes placed midway between the front and back edges of the heel, (b) two spikes placed towards the back edge of the heel.](image)

Slipping may also be affected by the height of the spikes, illustrated in Figure 5. The spikes used were cylindrical (1.5 mm diameter) and the two heights selected for testing were 2 mm and 4 mm, representative of commercially available ice cleats.
3.3 Footwear and Instrumentation

Three pairs of winter boots (women’s size 6, women’s size 8, men’s size 10) were modified to allow for spikes to be inserted in various positions in the sole. The boot modifications included removing the existing heel tread and attaching a new heel (Vibram Lug Heel Lift - Style 3359) that had metal plates embedded in the rubber (Figure 6). One metal plate was located mid-heel and another was located at the rear of the heel, and each metal plate had two threaded holes positioned close to the edge of the sole. Threaded spikes 2 mm and 4 mm tall were made to screw into the plates through the rubber sole.

An active infrared motion capture system (Visualeyez, PhoeniX Technologies Incorporated, Burnaby, Canada) recording at 100Hz was used to track the position of foot markers during all trials. Markers were placed on the lateral toe and heel of each boot as shown in Figure 7. Static landmarking trials were performed before walking trials began to record the position of the rearmost bottom edge of the boot heel (point A in Figure 7) relative to the foot markers,
assuming the boot to be a rigid segment, and the edges of each walkway relative to the lab origin (for use when animating the kinematic data, described in Section 3.7.1.). A pointed probe instrumented with markers in fixed positions relative to the tip was used for landmarking trials, as the location of the tip in space can be determined from the marker orientations.

![Figure 7: Markers used to track the position of the foot are shown circled in red and the location of the heel landmark recorded before trials is shown as a solid circle labeled point A.](image)

Force plates (Advanced Mechanical Technology Inc., Watertown, USA) recording at 1000Hz were used to measure ground reaction forces during steps on level ice and provide the timing of heel contact and toe-off gait events. Due to laboratory limitations, it was not possible to use force plates under the icy ramp walkway to aid in detection of gait events. A footswitch system was therefore developed using force-sensing resistors – FSRs (Interlink Electronics, Camarillo, USA) – connected in a circuit similar to that shown in Figure 8 below.
Before participants put boots on, FSRs were taped to their bare feet with two FSRs connected in parallel taped under the heel of each foot and one FSR placed under the great toe of each foot (Figure 9), with $R_M = 10k \, \Omega$ for the heel sensors and $R_M = 5.1k \, \Omega$ for the toe sensors. The footswitch voltage output was recorded at 1000Hz. A MATLAB (The MathWorks Inc., Natick, USA) script was developed to determine heel contact times for each participant from the footswitch data based on a sharp increase in voltage as the heel made contact with the walkway. Time periods where the voltage increased from an initial value of approximately 0V (heel not in contact with the ground) to a final value greater than or equal to 3.5V (heel in contact with ground) were identified. The time of heel contact was then defined as the first point following the plateau at 0V where voltage began to rise (slope greater than 5 V/s). The timing of the footswitch-determined heel contact events on the level walkway was compared to the times determined from the force plates to verify the footswitch accuracy. Footswitch heel contact times were within an average of 10 ms (i.e. one frame of kinematic data) of the heel contact events determined using the force plates for steps on the level ice. An electronic trigger was used to synchronize the force plate and footswitch data collection with the motion capture system collection.
3.4 Experimental Set-up

Experiments were performed in ClimateLab at the Toronto Rehabilitation Institute, which can maintain temperatures as low as -20°C to simulate winter conditions with ice and snow. Two walkways were used for testing (Figure 10): 1) a walkway with level wood, level ice and two embedded force plates to capture ground reaction forces, and 2) an ice ramp (5° slope) with a ceramic tile landing at the top and a wooden landing at the bottom. The total length of the ramp and its landings is 3.3 m, while the level walkway is 3.2 m long.

Ice hardness and wetness have been shown to impact slipperiness, with wet ice and softer ice at temperatures above -10°C demonstrating lower available coefficients of friction. During trials the ambient temperature was kept at 4°C with a thin layer of water on the icy surfaces to create a slippery soft, wet ice condition.
Figure 10: Experimental set-up, with dimensions in metres. In the middle of the level walkway are two force plates with ice mounted on top, whose positions are shown as FP1 and FP2. The sloped walkway had a level ceramic tile landing and a 5° slope ice ramp, with a wooden landing at the bottom.

3.5 Experimental Design

A 2x2x3 repeated measures factorial design was used with an additional control condition. The independent variables were spike position (middle and rear of heel, A and B as shown in Figure 4) and spike height (A and B as shown in Figure 5), as well as walkway surface (level ice, downhill icy slope, uphill icy slope) while the additional control condition tested the winter boot with no spikes in the sole on each walkway surface.

Five different footwear conditions were tested by each participant, and a sixth practice condition was performed at the start of data collection since gait during the very first set of trials could have differed significantly from subsequent trials. The order of conditions was randomized and the footwear configuration that was tested twice (i.e. used in the practice trial) was balanced across participants. An example testing plan showing the order of footwear configurations, surface tested and starting direction on the walkways is shown in Table 1. Each footwear condition was tested on both the level and sloped walkway before the participant changed to the next footwear condition, and the surface on which they started (level or ramp) and the direction in which they began walking on each surface (e.g. up or down the ramp) was randomized. If the surface order was, for example, level-ramp then the participant walked back and forth on the level walkway
three times before walking up and down the ramp three times. If the starting direction on the ramp was up, then for ramp trials the participant began at the bottom of the ramp, walked up the slope, turned on the ceramic landing and walked back down the slope; this was considered one trial. The participant would then walk up and down the ramp twice more for a total of three ramp trials.

**Table 1:** Combinations of spike configurations to be examined in each test session. Factors are walking surface (level, ramp up, ramp down), and footwear condition with spike position (A - middle and B – rear, as shown in Figure 4) and spike height (A - short and B – tall, as shown in Figure 5) being varied, in addition to a control condition with no spikes. The direction of walking was varied between sets of trials so that participants began either walking up or down the ramp, and the participant alternated between starting on the level walkway or the sloped walkway for each set of trials.

<table>
<thead>
<tr>
<th>Spike Height</th>
<th>Spike Position</th>
<th>Surface Order</th>
<th>Starting Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tall</td>
<td>Rear</td>
<td>Level - Ramp</td>
<td>Up ramp</td>
</tr>
<tr>
<td>Short</td>
<td>Middle</td>
<td>Ramp - Level</td>
<td>Down ramp</td>
</tr>
<tr>
<td>Short</td>
<td>Rear</td>
<td>Ramp - Level</td>
<td>Up ramp</td>
</tr>
<tr>
<td>Tall</td>
<td>Middle</td>
<td>Ramp - Level</td>
<td>Up ramp</td>
</tr>
<tr>
<td>Tall</td>
<td>Rear</td>
<td>Level - Ramp</td>
<td>Down ramp</td>
</tr>
<tr>
<td>No spikes</td>
<td>Level - Ramp</td>
<td>Down ramp</td>
<td></td>
</tr>
</tbody>
</table>

**3.6 Protocol**

Coats, hats and gloves were provided to participants to keep them warm in the ClimateLab and a safety harness was worn to prevent contact with the ground in the event of a fall. Participants wore an anti-slip device with sandpaper-like aluminum oxide strips under the forefoot only (Grips-Lite by Winter Walking, Horsham, USA – with the heel of the device removed) during all trials – including trials where the boot was tested with no spikes in the sole - to prevent toe slips, as these slips could have impacted confidence during gait or heel contact of the following step. Participants tested each of the footwear configurations while walking at a self-selected pace on the surface conditions to be tested.

The surface order was randomized so that subjects performed either level walkway or ramp
trials first, and starting direction was randomized so that subjects started on either end of the walkway for level trials and began walking up-slope or down-slope for ramp trials. Participants did three trials (where one trial consisted of up and down the ramp, or back and forth on the level walkway) for each footwear and walkway combination. During each level trial participants took one step on the wooden platform, one step on each ice-covered force plate and one step on the second wooden platform before turning and repeating in the opposite direction (Figure 11a). For each ramp trial, participants took one step on the ceramic tile, as many steps as were required to walk down the icy ramp and one final step onto a wooden landing at the bottom of the ramp before turning (Figure 11b), or vice versa if the starting direction was not down the slope.

![Figure 11a: Level Walkway](image)

![Figure 11b: Sloped Walkway](image)

Figure 11: The a) level and b) sloped walkway are shown with circles to indicate where on the platform the participant stood at the beginning and end of the trials and turned while changing direction. Approximate foot placement during each step is indicated with an X, though it should be noted that the number of steps taken on the icy ramp varied between participants and trials.

After both the sloped and level walkway conditions had been completed, the participant left the laboratory to complete a short questionnaire (Appendix A) measuring their perception of slipping for the surfaces and footwear conditions just tested while the configuration of spikes in their boots was changed. Participants were not informed of the footwear condition they were testing until the end of that set of trials.
3.7 Data Processing

3.7.1 General Processing

Visual3D (C-Motion Inc., Kingston, Canada) software was used to perform initial processing of the kinematic data as well as to animate the recorded motion of the feet during trials. Position data were filtered using a fourth-order low-pass Butterworth filter ($f_c = 6$Hz, determined from residual analysis in MATLAB) after outliers were removed, and missing data points were interpolated using a cubic spline. Outliers were determined using the distances between markers on the boot during a static trial with no marker movement. Because the boot was assumed to be a rigid body, if the resultant distance between markers was $2\text{ cm}$ greater or less than the distance calculated during the static trial then the position data for the offending marker and frame was removed. Left and right foot segments were defined using the position of markers tracked during the experiment, while walkway surfaces and virtual heel landmarks on each foot were created in the model (shown in Figure 12) from the data collected in static landmarking trials. The heel landmark used was the rearmost bottom edge of the boot heel, as an approximation of the point of initial boot contact with the walkway. Kinematic parameters (virtual heel position and velocity, angle between the foot and walkway and foot angular velocity) were exported from Visual3D and combined with force plate data in MATLAB for further analysis.

Using MATLAB, force plate data were filtered with a fourth-order low-pass Butterworth filter with a cut-off frequency of 45Hz, determined from residual analysis, and the force plate and footswitch data were down-sampled from 1000Hz to 100Hz in order to align with the collection frequency of the kinematic data. Heel contact and toe-off were identified from force plate data as the first and last points with a vertical force $10\text{ N}$ above the mean of unloaded data, respectively. The slip distance was determined using the gait event timing in conjunction with the kinematic output from Visual3D, and was measured as the horizontal (antero-lateral or antero-medial) distance traveled by the heel from slip onset to slip end. Backward motion of the heel was not included in the slip distance measurement. Refer to section 3.7.2 below for slip onset and slip end definitions. The vertical and horizontal
Ground reaction forces (as a percentage of participant weight) and foot-floor angles were identified at the time of slip onset determined using each slip definition.

Figure 12: Animated view of the sloped walkway and foot markers in Visual3D. The image depicts a step where the participant is walking down the ramp, with the left foot flat on the ceramic platform and the right foot stepping onto the ramp. Walking direction (i.e. direction of progression) is indicated on the image.

3.7.2 Data Analysis

Two measures of slip distance were calculated based on definitions of slip onset found in the literature. The slip onset used in the majority of slip studies is the point of initial heel contact (HC slip), while an acceleration-based slip onset is defined as the first instant in time after heel contact at which heel acceleration increases above zero while the heel is moving forwards (acceleration slip). For both slip distance measures used in this study, slip end was defined as the point where the heel velocity reached approximately zero. While
using the heel contact definition of slip onset a slip distance threshold of 1 cm was used to classify a step as a slip because steps on the wooden platforms at either end of the level ice walkway exhibited heel contact slip distances of up to 1 cm. The same distance threshold of 1 cm was used to classify steps as slips using the acceleration definition of slip onset in order to ensure that slips were not erroneously detected as a result of noise in heel position data. Slip distances measured for acceleration slips that were attributed to marker noise were observed to be less than 1 cm; representative data illustrating one such slip is provided in Appendix B (Figure B1).

The processed data were used for two separate analyses: comparisons between the five footwear conditions tested, and a comparison between two slip onset definitions. The comparison of slips between footwear conditions was done using the acceleration slip definition. The comparison between the two methods of defining a slip, HC slip and acceleration slip, was performed across participants and footwear conditions to identify the effect of slip onset definition on the number and magnitude of slips.

### 3.7.3 Statistical Analysis

A linear mixed-effects model was used to assess the effect of slip definition on the number of slips identified during gait on level ice. The outcome of each step taken by the participants was classified as ‘slip’ (1) or ‘no slip’ (0) for each slip definition. The mixed model was used to account for random effects associated with repeated measures being performed on each participant. A significance level of $p < 0.05$ was used in the analysis. Statistical analysis comparing slips between footwear conditions on level and sloped ice was not performed because of the small acceleration slip sample size.
Chapter 4
Results

4.1 Terminology

For all results, the following terminology will be used in describing walkway and footwear conditions as well as slip definitions:

Walkway:

- **Level** condition: steps occurring on the level ice
- **Ramp condition/sloped** walkway: steps occurring while walking *down* the icy slope

Footwear:

- **None** condition: footwear with no spikes in the sole
- **TM** condition: Tall spikes located in the **M**iddle of the heel
- **TR** condition: Tall spikes located at the **R**ear of the heel
- **SM** condition: Short spikes located in the **M**iddle of the heel
- **SR** condition: Short spikes located at the **R**ear of the heel

Slips:

- **HC** slip: a heel slip (>1 cm) measured using the heel contact definition of slip onset
- **Acceleration** slip: a heel slip (>1 cm) measured using the acceleration definition of slip onset
4.2 Ice Cleat Design

Five different footwear conditions were tested during experiments: boots with no spikes in the sole (None), boots with tall spikes in the middle or rear of the heel (TM and TR, respectively) and boots with short spikes in the middle or rear of the heel (SM and SR, respectively). For all comparisons of slips between footwear conditions, the acceleration slip onset definition was used. There were no slips observed walking up the ice ramp and therefore all discussion of slope trials is limited to steps down the ice ramp.

There were few slips observed during gait on level ice (Figure 13) or the icy slope (Figure 14). Slips occurred in all footwear conditions, though the footwear condition observed to have the greatest number of slips on both the level and sloped ice was the boot with no spikes. No slips were identified on level ice while participants were testing the TR condition, and there were no slips on the ramp while participants were testing the TM condition. Because of the small number of slip samples, a statistical analysis was not performed to compare footwear conditions. Qualitatively, there were no obvious trends in the number of slips or slip distances across footwear conditions. The slip frequency for each footwear condition, presented as a percentage of the number of steps analyzed, is shown in Table 2.

**Table 2**: Slip frequency for each footwear condition, as a percentage of the number of steps analyzed for that condition.

<table>
<thead>
<tr>
<th></th>
<th>Level Walkway</th>
<th></th>
<th>Sloped Walkway</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total Steps</td>
<td>Slip Frequency (%) of</td>
<td>Total Steps</td>
<td>Slip Frequency (%) of</td>
</tr>
<tr>
<td></td>
<td>Analyzed</td>
<td>Steps Analyzed</td>
<td>Analyzed</td>
<td>Steps Analyzed</td>
</tr>
<tr>
<td>None</td>
<td>96</td>
<td>3.1</td>
<td>110</td>
<td>6.4</td>
</tr>
<tr>
<td>TM</td>
<td>96</td>
<td>1.0</td>
<td>91</td>
<td>0</td>
</tr>
<tr>
<td>TR</td>
<td>84</td>
<td>0</td>
<td>101</td>
<td>3.0</td>
</tr>
<tr>
<td>SM</td>
<td>72</td>
<td>1.4</td>
<td>82</td>
<td>3.7</td>
</tr>
<tr>
<td>SR</td>
<td>92</td>
<td>1.1</td>
<td>92</td>
<td>5.4</td>
</tr>
</tbody>
</table>
Investigation of force plate data (recorded for steps on level ice only) and the angle between the foot and walkway (for both level and ramp trials) indicated that all slips that occurred while the participant was wearing spikes began after the foot had rotated to flat. The participant’s full body weight (BW) was on the slipping foot and their trailing foot had lifted off of the ground.

When there were no spikes in the footwear (‘None’ condition), it was also generally observed that slips occurred after the slipping foot was flat with full body weight transferred to that foot. However, there were three occasions where the foot had not yet rotated to flat before slip onset (foot-floor angle: 8° on level ice, 5° and 13° on icy slope). For the slips on level ice, the participant had only loaded from 73-100% BW onto the slipping foot before slip was initiated (average 88% BW, SD 14%).
Figure 13: Slips on the level walkway, determined using the acceleration definition of slip onset. ‡ Note: A total of three slips occurred in the None (no spike) condition – two slips overlap as they had very similar slip distances (approximately 2.8 cm). A slip is heel displacement > 1 cm and slips shown are across all participants.
Figure 14: Slips on the sloped walkway, determined using the acceleration definition of slip onset. A slip is heel displacement > 1 cm and slips are shown across all participants.
4.3 Slip Definition: Heel Contact versus Acceleration Slip Onset

Two measures of slip distance were calculated based on definitions of slip onset found in the literature. The slip onset used in the majority of slip studies is the point of initial heel contact (HC slip), while a subset of studies has used an acceleration-based slip onset (acceleration slip) defined as the first instant in time after heel contact at which heel acceleration increases above zero. A slip distance threshold of 1 cm was used, above which steps were classified as slips, as described in Section 3.7.2. The number of slips and slip distances observed using each definition of slip onset were compared.

4.3.1 Number of Slips

The gold standard for determining the time of heel contact is to measure the timing of the first point of vertical force using force plates, which were only used during level trials. For this reason the discussion of number of slips detected using the HC slip definition is limited to trials on the level walkway.

There was a significant difference ($F_{1,595} = 160.38, p < 10^{-6}$) in the number of slips measured for each participant using the heel contact definition of slip onset (135 slips) and the acceleration definition of slip onset (six slips) during gait on level ice, shown in Figure 15 and Figure 16. The effect of spike height, position and their interaction was not significant (height: $F_{1,595} = 0.032, p=0.86$; position: $F_{1,595} = 0.404, p=0.53$; height*position: $F_{1,595} = 0.074, p=0.79$). Using the heel contact definition of slip onset, there were slips greater than 10 cm that were measured but were not detected by the participant or the researcher in the room with the participant. The largest undetected HC slip measured 18 cm. These steps were also not identified as slips using the acceleration slip onset definition, and produced no visible signs of gait disturbance upon review of the experiment video recordings or the animated kinematic data. All of the six measured acceleration slips were perceived as slips by the participant, as noted in the questionnaires.
completed following each trial, and were visible upon review of the video and animated kinematic data.

The occurrence of slips varied greatly between participants, shown in Table 3. Approximately two-thirds of slips on level ice were from one participant’s trials, and nearly half of the ramp slips were attributed to a different participant.

**Table 3**: Number of slips attributed to each participant on the level and ramp walkways using the acceleration slip onset definition, and on the level walkway using the heel contact slip onset definition.

<table>
<thead>
<tr>
<th>Participant</th>
<th>Weight (N)</th>
<th># Acceleration Slips</th>
<th># Heel Contact Slips</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Level</td>
<td>Ramp</td>
</tr>
<tr>
<td>S01</td>
<td>582</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>S02</td>
<td>506</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>S03</td>
<td>626</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>S04</td>
<td>581</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>S05</td>
<td>813</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>S06</td>
<td>626</td>
<td>0</td>
<td>8</td>
</tr>
</tbody>
</table>

**4.3.2 Slip Distance**

Due to the large discrepancy in the number of slips identified using the HC and acceleration slip definitions (Section 4.3.1), for steps where an acceleration slip was indeed detected the slip distances measured using each definition were also compared. However, owing to the small number of acceleration slips observed on level ice, the comparison of slip distances was extended to include ramp trials. The timing of heel contact in ramp trials – determined from footswitch data – was verified by examining the timing of approximate zero vertical velocity and position of the heel. The accuracy of the footswitch heel contact events during level trials was also compared to force plate heel contact events, and was determined to be accurate within on average one frame of kinematic data. Statistical analysis was not performed because of the small acceleration slip sample size.
4.3.2.1 Level Walkway

Of the six steps on level ice where there was an acceleration slip detected, three had kinematic data for the heel at the time of heel contact. For these steps, the resultant slip distances measured using the HC and acceleration slip onset definitions were fairly similar, with differences of less than 0.6 cm.

4.3.2.2 Ramp

For steps down the icy ramp where there was an acceleration slip detected, there were a number of large observed differences between the resultant slip distances measured using the HC and acceleration slip onset (Figure 17); the HC slip distance exceeded the acceleration slip distance for matched steps by an average of 7 cm (SD 5 cm). Though steps where the heel was not visible at the exact frame of heel contact were not included in this calculation of difference in slip distance, they were included in Figure 17 using the first visible frame after heel contact (within two frames) to estimate heel position at contact; these steps are noted on the figure. All of the slips detected using the acceleration slip definition were also detected by the participant and were visible upon review of the video and animated kinematic data.
Figure 15: Slips on the level walkway, determined using the heel contact definition of slip onset (* denotes a slip of 18 cm for S05). Steps where both a HC slip and acceleration slip were detected are overlaid with a red square. Each plot corresponds to a different participant (S01 = Subject 01).
Figure 16: Slips on the level walkway, determined using the acceleration definition of slip onset. Each plot corresponds to a different participant (S01 = Subject 01).
Figure 17: Differences in slip distance measurements between the acceleration and heel contact definitions of slip onset are shown for matched steps on the sloped walkway; only steps with a measured acceleration slip were used. Slips are shown across all participants but are separated by footwear condition. Positive differences indicate the heel contact slip distance was larger and ‡ denotes a slip where the first visible frame after heel contact (within 2 frames) is used to estimate the HC slip distance.
4.4 Heel Position During Heel Contact and Acceleration Slips

The following figures illustrate heel position during representative trials with HC-only slips or both a HC and acceleration slip observed.

The largest HC-only slip observed, with a slip distance of 18 cm, is shown in Figure 18. The heel contact event was confirmed using the vertical position and velocity of the heel and the footswitch data to ensure that it had not been detected in error, and upon review of the animated kinematic data the path of the heel looked like a typical heel strike or potential heel drag rather than an unexpected slip.

Figure 18: Heel position in the direction of progression is shown for the 18 cm slip detected using the heel contact slip definition. Point of heel contact is shown at frame 0.
Representative data for the horizontal heel position (in the direction of progression) at heel contact during typical steps with no qualitatively observed slips or measured acceleration slips are shown in Figure 19 and Figure 20. A clear decrease in velocity can be observed leading up to heel contact and the foot either slid forwards and then backwards after heel contact or slid only forwards before coming to a stop.

**Figure 19:** Heel position in the direction of progression for a step with a forward-backward sliding motion at heel contact. Heel contact is shown at frame 0.

**Figure 20:** Heel position in the direction of progression for a step with only forward motion at heel contact. Heel contact is shown at frame 0.
Representative heel position data for steps where a slip occurred after heel contact are shown in Figure 21. The data is consistent with the heel behaviour described by Lockhart et al. (2000) with a decrease in horizontal heel velocity prior to contact followed by a forward slip as the forefoot rotates to flat and the body’s centre of gravity shifts towards the sliding heel.

**Figure 21:** Heel position in the direction of progression for a step with a slip (detected using the acceleration slip onset) occurring after heel contact. Heel contact is shown at frame 0, and the acceleration slip start and slip end are also indicated on the plot.

The step shown in Figure 22 below involved a slip initiated soon after heel contact on the icy ramp, with no period of zero velocity between heel contact and slip start.
4.5 Indicators of Cautious Gait

In order to assess whether participants may have walked cautiously during trials, three gait parameters were examined: foot-floor angle at heel contact, step length and walking speed. The average foot-floor angles at heel contact on level ice and sloped ice were $21.4^\circ$ (SD $7.2^\circ$) and $15.7^\circ$ (SD $8.0^\circ$), respectively. Step length was on average 0.59 m (SD 0.04 m) on level ice and 0.48 m (SD 0.08 m) on the icy ramp, while average walking speed was 0.95 m/s (SD 0.14 m/s) on level ice and 0.79 m/s (SD 0.18 m/s) on the ramp.
Current research on the properties of winter footwear that impact their slip-resistance is limited, particularly with respect to the design of anti-slip devices such as ice cleats. One aim of the present study was to examine the effects of anti-slip footwear design characteristics on their performance on slippery winter surfaces. Studying variables such as spike height in ice cleats can also assist in developing guidelines for their safe use by consumers, for instance the height at which the spikes may need to be replaced after becoming worn with repeated use or the types of devices that may be appropriate for use on level versus sloped icy surfaces. However, there are different approaches used in the literature to identify and measure slips. Therefore an additional aim of the current study was to evaluate and compare slip outcomes measured using two different slip definitions.

5.1 Ice Cleat Design

There are various types of ice cleats available to consumers, including cleats with spikes along the entire length of the foot and cleats that have spikes under the forefoot or heel only. Though slips can occur both at heel contact and toe off, heel contact is considered the most dangerous phase of the gait cycle in terms of slip risk. Slips that occur at heel contact are not only more frequent, but can also be more hazardous because they result in a backwards fall (Grönqvist 1999; Strandberg and Lanshammar 1981; Redfern and DiPasquale 1997). For this reason, the current study focused on characteristics of spikes in the heel. It was hypothesized that spikes located closer to the rear edge of the heel would help prevent slips occurring soon after heel contact and might add some additional protection from slipping compared to spikes located in the middle of the heel. This result was not observed, as slips occurred in footwear conditions with spikes in the middle or rear of the heel. It should be noted that the acceleration slip onset definition, where a slip begins at the first point of increasing positive acceleration of the heel following heel contact (with the stipulation that heel movement must be in a forward direction), was used to compare slips between footwear conditions. Using this definition, the total number of slips observed across all trials was quite low, particularly on level ice. The
footwear with the most observed slips on both level and sloped ice was the boot with no spikes in the sole, but slips were nonetheless measured in all footwear conditions. The occurrence of slips varied greatly between participants; 67% of level slips were attributed to one participant, and 44% of ramp slips were attributed to a different participant (Table 3). There was also a participant who did not slip (using the acceleration slip definition) in any trial.

As evidenced by the results, there was no clear trend in the data indicating that one type of cleat design was superior to another, although there were fewer slips with spikes in the middle of the heel compared to spikes in the rear of the heel for steps on the icy ramp. It was interesting to note that for all of the slips involving footwear with spikes in the sole the foot had already rotated to flat before the slip began and the trailing foot had either lifted off the ground or almost lifted off the ground, meaning most or all of the participant’s body weight was already transferred to their slipping foot before slip initiation. This was confirmed from force plate readings for the level trials. There were, however, some slips noted before foot-flat for the footwear with no spikes in the sole. Though a greater slip sample size would be required to draw conclusions from these observations, the differences in slipping between footwear conditions with and without spikes demonstrates the potential for spikes in the heel to prevent dangerous slips from occurring between heel contact and foot-flat.

Given that slips were detected even with spikes in the heel of the boot (rear or middle), this may indicate that spikes placed solely in the heel are not adequate for preventing slips - particularly on sloped surfaces – and that spikes in the forefoot are important for preventing slips that are initiated once the foot has rotated to flat. Since there are commercially available anti-slip devices that have spikes located under only the heel, it is important to understand how these devices would perform on not just level ice but also icy downward slopes where shear forces increase with the angle of the ramp (Redfern and DiPasquale 1997). It is possible that as an individual’s centre of pressure progresses further forward on the foot than the location of the ice cleats there is not enough weight on the spikes to maintain sufficient penetration into the ice surface, and they are unable to
counteract the high shear forces down the slope. Previous work examining the slip-resistance of winter anti-slip devices is limited, with a small number of studies and very little quantitative data. Gard and Berggard (2006) examined three different anti-slip device designs that used chains across the entire foot, studs in the heel or studs in the forefoot and found that the device with studs in the heel only received the highest ratings overall for walking safety and balance. However, the main outcomes were participant perception of safety and balance and observations of walking posture and movements from video recordings rather than quantitative measurements of slip. The anti-slip devices also did not all use studs in the sole and they were tested over level ground, which may limit the applicability of the observed results to more challenging terrain.

The study results may be limited by the fact that participants likely walked more cautiously than normal because they were aware of the slippery surface. Individuals typically decrease their foot-floor angle at heel contact in anticipation of slippery flooring (Cham and Redfern 2002b). For the participants in this study, the average foot-floor angles at heel contact on level ice and sloped ice were 21.4° (SD 7.2°) and 15.7° (SD 8.0°), respectively during steps in which an acceleration slip was observed. The foot-floor angles on level ice are comparable to foot-floor angles reported for normal gait on dry surfaces in the literature of 22-23.5° on level ground (Strandberg 1983; Cham and Redfern 2002b), while the foot-floor angle on the ramp was much smaller than the 26.4° reported on a 5° slope by Cham and Redfern (2002b). The average step length and walking speed for level trials, 0.59 m and 0.95 m/s respectively, was similar to reported values for gait on dry level surfaces that ranged from 0.54 – 0.6 m for step length and 0.97 – 1.23 m/s for walking speed (Redfern and DiPasquale 1997; Oberg et al. 1993). The average step length and walking speed for gait down the ramp, 0.48 m and 0.79 m/s respectively, were lower than average reported values of 0.53 - 0.58 m for step length and 1.0-1.1 m/s for walking speed down a 5° slope (Redfern and DiPasquale 1997; Sun et al. 1996). Decreased foot-floor angle, step length and walking speed could be indicators that participants were more cautious on the downward slope and may have adapted their gait because they were aware of the slippery surface (Cham and Redfern 2002b). It was also qualitatively observed during trials that some participants walked carefully even though
they were instructed to walk as normally as possible. This was a limitation of the study and is discussed in more detail below.

5.2 Slip Measurement

To date, several researchers have focused on slip distances during walking as an indicator of slip severity and the risk of falls (Cham and Redfern 2002a; Tsai and Powers 2013; Brady et al. 2000; DiDomenico et al. 2007; Lockhart et al. 2000; Strandberg and Lanshammar 1981). Slip onset is typically defined as the time of heel contact (Cham and Redfern 2002a; Moyer et al. 2006; Brady et al. 2000) and slip distances are measured from this point until slip end, defined as the point where the heel stops moving (horizontal velocity approximately equal to zero). Heel displacement thresholds used for determining whether a step is a slip or not are generally either 1 cm (Perkins 1978) or 3 cm (Leamon and Li 1990), as these have been suggested as the thresholds below which an individual will likely not perceive that they are slipping. Slip distances are used not only to characterize steps as slips, but also to evaluate the severity of slips (Brady et al. 2000). Higher slip distances are associated with more dangerous slips, and it has been suggested that slip distances of greater than 10 cm are likely to result in a fall (Perkins 1978; Strandberg and Lanshammar 1981).

Given the reliance of the HC slip definition on an accurate determination of heel contact and tracking of the heel, there is surprisingly little information provided by a number of studies about the specific method used to determine heel contact or the location chosen to represent the heel. Because the velocity of the heel right at heel contact can still be quite high (0.14-2.75 m/s from Redfern et al. 2001) the impact of an improperly identified heel contact time on overall slip distance as well as peak slip velocity could be significant. When the heel contact slip definition is used in slip measurements but no information is provided to explain the identification of heel contact it can become difficult to assess the accuracy of slip distances and compare values between studies. The location of the heel point used in measurements of heel position and velocity is sometimes unclear and when specified is not always located at the approximate point of contact between the footwear and the walkway, i.e. the bottom rearmost portion of the heel. A heel point located higher
on the foot may increase the slip distance measured from heel contact because of the horizontal linear component of rotation as the foot rotates to flat. When specific distance thresholds are used to identify steps as slips (e.g. 1 cm) or likely falls (e.g. 10 cm), any inflation of slip distance could impact the results of these classifications and make comparison of results between studies more difficult.

5.2.1 Slip Onset Definition

The heel position data from the experiments comparing different ice cleat configurations were analyzed using each of the aforementioned methods for slip detection: slip onset defined as the point of heel contact (HC slips) and slip onset defined as the first point of forward positive heel acceleration following heel contact (acceleration slips).

There were 135 HC slips identified on level ice, while there were only six slips identified on level ice using the acceleration slip definition. The 129 steps where a slip was measured using only the HC slip definition were not detected by the participant or researchers, and video review showed no visible gait disturbance during these trials. The largest HC-only slip observed had a slip distance of 18 cm (Figure 18); the heel contact event was confirmed and the path of the heel during this and the other HC-only slips looked like a typical heel strike or potential heel drag rather than an unexpected motion of the heel due to slipping. Using heel contact as a start point for measuring the slip distance is likely to produce ‘false positives’ where a slip is detected even though no unintended and unexpected motion of the heel has occurred. This could have been exaggerated by participants walking cautiously and dragging their heel at heel contact more than if they were walking confidently on dry ground, but a robust definition of slip must be able to account for different gait characteristics and variable heel contact behaviour.

In contrast to the HC slip method, all of the slips detected using the acceleration slip onset had been noted as slip trials by participants in their questionnaires and were visible from animated kinematic data. As such the acceleration slip definition appears to be less prone to error than the HC slip definition. There were no slip trials noted by participants
or observed during video review of trials that were not also detected using the acceleration slip definition.

A potential shortcoming of the acceleration slip definition could be its ability to detect slips that occur at or very soon after heel contact. If there was no braking of the heel prior to heel contact and rather the heel continued to slide forwards at a constant velocity once it contacted the ground then there would be no detectable change in acceleration and the slip would be missed. However, from the data collected during this study it was observed that the acceleration slip definition was able to detect a number of slips occurring very soon after heel contact. The step shown in Figure 22 involved a slip after heel contact on the icy ramp and it can be observed that there is no period of zero velocity between heel contact and slip initiation, as had been observed in the majority of other slips (e.g. Figure 21). An attempt to slow the heel at impact can still be seen as an inflection point in the position of the heel after heel contact, and this is the point of acceleration slip onset. From qualitative observations of the step shown in Figure 22 during review of experiment video recordings and animated kinematic data, the participant appeared to slide their foot forward with a foot-floor angle of approximately zero at heel contact, rather than exhibiting a typical heel contact where the foot contacts the ground at an angle before rotating to flat. This could be considered a ‘worst-case scenario’ for slip detection using the acceleration slip onset because one would not expect a significant decrease in horizontal heel velocity at the beginning of the foot slide.

Although the present study did not record any slips that began with a constant-velocity heel contact, this type of slip may still be possible and would be missed by the acceleration slip onset. It is recommended with any definition of slip and measurement of slip distance that video recordings, experimental notes by the researchers observing the experiment and participant perceptions of slipping be used in conjunction with kinematic data to identify slips. It would also be worthwhile to incorporate a measure of instability in order to not only identify slips but also assist with determining the severity of a slip and its associated recovery reactions. Methods that have been developed to detect sudden reactions to slipping include measuring trunk accelerations (Hirvonen et al. 1994) or
tracking the position of the approximate centre of mass to aid in the detection of gait instability (Lee et al. 2006), which could be easily incorporated into a slip detection procedure.

For the present study, slip end was defined as the point of approximately zero horizontal heel velocity. This is in contrast to the slip end point of maximum horizontal heel velocity used by Lockhart et al. (2000) which the authors used in part to account for the fact that participants may have relied on the safety harness to avoid falling, influencing outcomes like slip distance and velocity. In the current study, self-report was used to determine if participants used the safety harness at any point during a slip, as well as qualitative observations made by researchers during the experiment. None of the participants were observed to have used the harness to arrest a fall. However, it is worth noting that during ramp trials participants would on occasion slide to the end of the ramp and that as a result slips occurring at the top of the ramp that continued to the bottom would have a larger slip distance than slips that were initiated at the bottom of the ramp. The appropriate definition for slip end may be an area to investigate in future work.

5.3 Limitations

Data was collected for a small number of participants, which limited the conclusions that could be drawn from the study. Ten participants were recruited for the study and completed all walking trials, but missing marker position data at crucial time points such as the point of heel contact led to only six participants’ data being usable. The number of slips experienced by each participant was also quite small, particularly on level ice, further complicating the matter of small sample sizes. It was observed that several participants walked somewhat hesitantly during trials although they were instructed throughout experiments to walk as naturally as possible. It has been shown in previous studies that anticipation of slippery surfaces leads to individuals adapting their gait in an attempt to mitigate the risk of slipping (Cham and Redfern 2002b). An attempt was made to make participants more at ease during trials by providing a practice set of trials at the start of collection to become accustomed to the instrumentation and encouraging them to sit in the safety harness and allow it to hold all of their weight to confirm that it would
protect them in the event of a fall. For future experiments it is recommended to make the task more challenging by introducing distractions that could include counting tasks during the experiment so that participants are less focused on their walking and therefore demonstrate more natural gait. Developing a method of producing black ice to create an unexpectedly slippery surface may also achieve the desired effect of a more natural gait pattern.

The walkways used for the study were designed to fit into the small laboratory space and were therefore likely not long enough for participants to reach their normal walking speed. The use of force plates in the level ice walkway may have also constrained participants’ step length as they were required to step with only one foot on each force plate and were aware of the force plate positions. In future studies that use an acceleration definition of slip onset the heel contact event may not be as crucial and force plates may not be needed for heel contact detection, though some studies may require their use to measure coefficient of friction. The use of longer walkways would potentially allow for more natural step lengths as well as higher walking speeds. The small collection volume also meant that it was not possible to track markers located on the upper body, which could have allowed for a measure of instability to be made. In future work trunk accelerometers or upper body kinematics from motion capture could provide additional information about balance and instability during a slip.

The boots used in the experiment were kept at room temperature prior to testing. It has been shown that harder boot soles have lower friction values on ice compared to softer boot soles and cooling the boots could have resulted in a more challenging condition with a harder rubber sole. The boots were not kept in the cold laboratory in order to prevent participants’ feet from becoming cold, particularly as they were already exposed to cold temperatures over the course of the 2-3 hour experiment, but it could be beneficial to try chilling only the soles using cold water baths or chill the boots and provide participants with heat packs for use inside their boots.
Finally, spikes were used in the heel of the footwear but the only protection from slipping provided to participants under the forefoot was in the form of an anti-slip device using sandpaper-like aluminum oxide bands. During pilot testing, participants were initially wearing spikes in the heel as well as under the forefoot. Spikes under the forefoot would occasionally cause trips when they became caught at points of small height transitions or gaps in the walkway as the foot swung forward. Participants in the pilot trials noted that they adapted their gait to lift their foot higher over these gaps in an attempt to avoid tripping; this would have impacted the ability to measure natural heel contact during the full study and therefore spikes in the heel only were chosen for testing. However, there were small toe slips observed during experiments using the forefoot aluminum oxide bands that could have also impacted a participant’s comfort level on the slippery surfaces. Including short spikes under the forefoot rather than less effective forms of traction could improve participants’ confidence and therefore ability to walk naturally during trials.

5.4 Future Work

There is presently little research evaluating the effectiveness of anti-slip devices. Although there are standard tests for the slip-resistance of general footwear there is no mention of traction devices in, for example, CSA footwear standards. Given the variety of anti-slip devices available to pedestrians there is a need to understand how they impact an individual’s gait and how they should be designed and used. For example, there are ice cleats with only spikes in the heel available to consumers and therefore it is important to understand if there are surface conditions on which these devices are not appropriate for use. The results of this thesis indicate that spikes may be required under the forefoot to prevent slips on ice, particularly during gait down sloped walkways. A larger study involving greater numbers of participants and more challenging conditions that would produce more slips should investigate the performance of normal boots, ice cleats with spikes in the heel only, and cleats with spikes in both the heel and forefoot on sloped surfaces to determine if cleats with spikes in the heel only are adequate to prevent slips downhill. As an additional measure, the effect of the spike configuration on foot clearance and the number of trips would also be worthwhile to assess, as participants in
pilot studies who wore spikes under the forefoot complained of trips on uneven surfaces and walkways with gaps of similar size to those seen in sidewalks.

The present study was unable to challenge participants to the point of slips resulting in falls and there were few slips occurring before the foot was flat on the walkway. It was not possible to fully conclude whether this lack of slips was due to the presence of spikes in the heel or as a result of participants walking cautiously. A follow up study introducing participant distraction could test three different ice cleat conditions to evaluate the importance of spikes close to the rear of the heel: 1) two spikes in the middle of the heel, 2) two spikes in the middle of the heel and two spikes in the rear of the heel, to observe whether the addition of the rear spikes decreased the number of slips near heel contact, and 3) two rows of spikes in the middle of the heel, with two spikes per row (i.e. four spikes total) to control for number of spikes as a confounding factor. It would be necessary to first identify the conditions that resulted in observable slips with spikes in the middle of the heel to develop a demanding experimental set-up.

The finding that slips during spike conditions only occurred once the foot was flat on the ground with full body weight applied to the slipping foot (confirmed for level trials) opens the door to additional research investigating the location of the centre of pressure under the foot at slip onset and comparing this to the position of spikes in the sole. Examining the pressure distribution under the foot and the areas of the foot and shoe with the highest levels of pressure may allow for a more systematic placement of spikes in ice cleats if there was an observed relationship between the location of highest pressure on the sole and the point of slip initiation.

Finally, the mechanical test devices outlined in footwear test standards often attempt to simulate ‘typical’ values of gait parameters such as foot-floor angle, normal force, and sliding velocity in their evaluation of slip-resistance. It is necessary to ensure that these devices test not only biomechanically-relevant conditions, but in particular typical conditions at true slip onset. Performing additional research using the acceleration slip onset definition may help confirm the values currently used by test devices or else
provide the basis for alternative values for angle, normal force and sliding velocity to be incorporated into the standard footwear tests to better simulate conditions at slip initiation.

5.5 Conclusions

The findings of this thesis demonstrate that ice cleats located in the heel of footwear may help prevent slips at heel contact but highlight that spikes in the heel alone may not be sufficient to prevent all slips from occurring, particularly down slopes. Further research with a larger number of observed slips and greater variation in spike position and number of spikes is needed to confirm these initial results. A comparison of slip measurement techniques from the literature, namely the definition of slip onset, demonstrates that using the point of heel contact as slip start for measurements of slip distance can produce erroneous slip classifications and an inflated number of slips. The use of an acceleration-based slip onset definition proved to be a more robust technique for identifying slips. The standard (ASTM, ISO, CSA) methods for measuring footwear slip-resistance rely on the use of mechanical test devices. These devices should simulate gait characteristics at slip onset and therefore an accurate determination of true slip onset is imperative.

5.6 Significance of Contributions

Slips and falls are common for pedestrians during winter months. Anti-slip devices are commonly used by pedestrians but are not always effective at preventing slips, and there is limited research examining the optimal design for these devices. Commercially available ice cleats vary in the number, position, height and shape of spikes and it is not clear how these factors affect their ability to prevent slips. Developing winter footwear that has increased slip-resistance on variable winter surfaces will provide outdoor workers and pedestrians with greater protection from the risk of winter slip and fall accidents. The work presented in this thesis assessed how two factors – the height and position of spikes in the heel – affect number of slips and slip distances. Preliminary findings indicate that in general, spikes located solely in the heel may not be adequate to prevent slips during gait down icy slopes, but that they have the potential to prevent slips from occurring
between heel contact and foot-flat. The results also indicate that it may be important for future studies to investigate a possible relationship between slip onset and the location of the centre of pressure relative to the spikes at that time. A paper discussing ice cleat design and the findings from the analysis comparing footwear conditions will be prepared for submission to the journal Footwear Science.

One method of evaluating winter footwear performance and comparing different footwear designs is to identify slips that occur during gait and compare the number of slips and slip distances between footwear conditions. There are, however, various methods of defining and measuring slips used in the literature and there has been no discussion to date about which may be the most appropriate definition to use. It is important to identify the most robust and relevant technique for assessing slips, as this will ensure that the most meaningful methods are used to evaluate footwear designs. The current study compared the heel contact definition of slip onset to a heel acceleration-based definition. The results demonstrate that the choice of slip definition can have a significant impact on the number of slips measured, and use of the heel contact definition may greatly inflate the number and distances of slips identified. Several practical issues associated with the measurement of slips have also been identified. These findings will be included in a paper that is being prepared for submission to the journal Safety Science.
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Appendix A: Questionnaire

The questions below were provided to participants after each set of trials. During a set of trials, one footwear condition (e.g. tall spikes in rear of heel) was tested on both the level ice and sloped ice walkways. Upon completion of the trials, the participant was told which footwear condition they had just tested and was asked to fill out the questionnaire while they rested outside of the cold laboratory and their footwear was changed to the next condition by the researcher. Participants were asked to provide any details they could about slipping in the comments section.
Perception Questionnaire - To be completed following each footwear condition

Walkway Conditions (to be completed by researcher): __________
Footwear Configuration (to be completed by researcher): __________

For each surface, indicate if your toe and/or heel slipped while walking:

Level ice:     ☐ Toe slip(s)     ☐ Heel slip(s)
Level wood:    ☐ Toe slip(s)     ☐ Heel slip(s)
Level ceramic tile: ☐ Toe slip(s)     ☐ Heel slip(s)
Icy ramp:      ☐ Toe slip(s)     ☐ Heel slip(s)

Comments:
1. What difficulties did you experience when you were walking with this footwear?
____________________________________________________________________________________________
____________________________________________________________________________________________
____________________________________________________________________________________________

2. Other comments:
____________________________________________________________________________________________
____________________________________________________________________________________________
There were a number of trials where an acceleration slip was identified but was suspected to have been the result of noise in the heel position data, rather than an actual slip. The slip distances in these cases were below 1 cm, and as a result a slip distance threshold of 1 cm was applied to all acceleration slip results. The heel position data (in the direction of progression) for a representative case are shown in Figure B1. Upon review of the animated kinematic data for this step in Visual3D, it was observed that most of the foot markers remained stationary after the foot had rotated to flat while two markers drifted slightly before returning to their original positions. The marker displacements and velocities were not extreme enough for the position data to be removed as outliers. Since the heel position is defined relative to all of the (visible) foot markers, this small shift caused a displacement of the heel that was then identified as a slip by the acceleration slip definition. The slip distance from ‘slip start’ at the point of increasing positive acceleration to the point of ‘slip end’ where the heel position has reached a plateau (both noted on Figure B1) is approximately 0.4 cm.

**Figure B1:** Representative heel position data (in the direction of progression from one step illustrating a detected acceleration slip caused by noise in the marker data. Slip distance = 0.4 cm.